# Laser-radiation tolerance of promising materials of IR optics. Part 2. Methods of improving the laser-radiation tolerance and service life of optical elements

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Systematization of types and conditions for appearance IR material damages in wide-aperture laser beams based on the results of previous experimental investigations has allowed creation of a technological series of windows for $CO_2$ lasers with the output energy up to 25 kJ in the pulsed mode and the mean output power up to 100 kW in the repetitively pulsed mode. Technological and design methods have been developed to improve the laser-radiation tolerance of the IR materials.

The technology of production of optical elements is one of the most important factors determining the efficiency of laser optics. It involves two main stages: material production and its technological processing to make an optical element.

Improving the crystal growth technology, we can decrease the absorption coefficient at the working wavelength $\beta$ by decreasing the concentration of foreign inclusions in the crystal, since the total absorption coefficient is a mere superposition of the absorption coefficients of the material and structure defects. By now the works on improvement of the methods of optical crystals growth done at the State Optical Institute, Institute of Crystallography RAS, Physical Institute RAS, and Moscow State Institute of Steel and Alloys have led to production of materials, in which the concentration of Fe, Cu, Ti, Pb, V, Mn, Ni, Co, Cr, Ba, Ca, S, Si, and Al admixtures does not exceed $\sim 10^{-5}$ percent by weight, and the values of the absorption coefficients are close to the theoretically possible limits.[1,3]

Some material parameters can be improved not only in the process of material production. In particular, mechanical characteristics can be sufficiently increased by using the method of plastic deformation of single crystals with following re-crystallization. In this case, a fine-grain polycrystal structure is formed in the crystal, and material strengthening occurs due to hindered motion of secondary dislocations as a result of creation of intrinsic defects.

A method of thermomechanical treatment of large-size plates (up to 300 mm) made of alkali halide crystals (AHC) has been developed. As a result of polarization optical and microstructure studies it was found that the structure becomes most homogeneous after uniaxial deformation of single-crystal plates along the direction <001> with the rate of 0.07–0.2 mm $\cdot$ min$^{-1}$ up to the degree of deformation $\varepsilon$ = 10–25% at the temperature no higher than 200–300°C. Crystals strengthened in this way have the yield point $\sigma_p$ four to seven times higher than the initial single crystals.[1–4]

Investigations of laser-radiation tolerance of strengthened AHC showed that only uniaxial deformation strengthening leading to formation of the homogenous fine-grain structure does not impair the optical quality relative to the initial material. In this case, due to the increase of the material yield point, the thickness of optical elements can be decreased two to three times, and, consequently, the irradiated volume can be decreased too. As a result of manifestation of the dimensional effect, this significantly increases the laser-radiation tolerance of such elements and saves a considerable amount of materials.[1,5]

Under the exposure to cw laser radiation, destruction of strengthened AHC, as well as single-crystal materials, has the thermomechanical character and occurs as a result of gradual accumulation of internal thermoinduced stresses. Therefore, the increase in the mechanical strength of crystals leads to a significant increase in their laser-radiation tolerance and service life $t_p$ (Table).

**Table. Laser-radiation tolerance for cw laser radiation, mechanical and optical characteristics of deformation-strengthened KCl crystals**

| Thermomechanical treatment mode ($t$, $\varepsilon$) | $q$, kW$\cdot$cm$^{-2}$ | $t_p$, min | $\sigma_p$, kg$\cdot$mm$^{-2}$ | $\beta$(10.6 μm), cm$^{-1}$ |
|---|---|---|---|---|
| Single crystal | 3.75 | 25 | 0.18 | $2 \cdot 10^{-4}$ |
| 200°C; 20% | 6.25 | 150 | 1.2 | $8 \cdot 10^{-4}$ |
| 360°C; 50% | 3.75 | 120 | 0.86 | $2 \cdot 10^{-3}$ |
| 300°C;(20+20)% | 5 | 100 | 0.94 | $4 \cdot 10^{-3}$ |
| 400°C; (40+40)% | 5 | 90 | 0.75 | $8 \cdot 10^{-3}$ |
| 200°C; (10+10+15)% | 5 | 110 | 0.9 | $3 \cdot 10^{-3}$ |
| 400°C; (20+20+40)% | 5 | 60 | 0.67 | $2 \cdot 10^{-2}$ |

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The laser-radiation tolerance of optical elements can be increased through treatment by pulses of wide-aperture laser radiation of below-threshold intensity that performs “laser cleaning” of the surface. This method has some important advantages: first, it does not require additional production equipment – the laser-radiation tolerance of optical elements increases as a result of their irradiation by a laser, in the optical system they are used; second, laser processing can be performed every time immediately before sending working pulses; third, the technological method used is quite easy.

It was found experimentally that the multiple effect of single $CO_2$ laser pulses of microsecond duration with the energy density $W \le 2$–$3$ J·cm$^{-2}$ increases the surface damage threshold of optical elements and decreases the damage probability at below-threshold intensity of the laser radiation. This effect keeps for 1–3 h after irradiation and is most pronounced at the gap between pulses no longer than 15–20 min (Refs. 1 and 6).

The integral spectrum records of plasma formations arising at optical breakdown near the surface indicate that the surface is cleaned from adsorbents (first of all, water) after the first five to six laser pulses having close intensity and the gradual decrease in the intensity of the $H_\alpha$ line is observed. Streak photographs of plasma formations show that under the effect of double and triple microsecond-duration pulses with the intensity $q \ge 1.8$–$8 \cdot 10^6$ W · cm$^{-2}$ ($W \ge 5$–$20$ J·cm$^{-2}$) the plasma torch is “caught up” by the following pulses up to the gap between pulses ~ 50–100 μs, and the optical breakdown is also possible in ionized desorption products under the effect of the second and following pulses even at below-threshold radiation intensity (Fig. 1).[1]

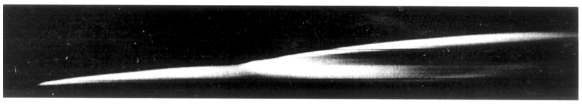

**Fig. 1.** Streak photograph of a plasma torch that arose under the effect of two laser pulses with the second pulse delayed by 8 μs with respect to the leading edge of the first pulse.

Keeping in mind that the optical breakdown leads to surface destruction, the optimal mode for laser processing of optical elements by microsecond pulses is the following:

– the energy density of laser radiation should not exceed the threshold value of optical breakdown (for AHC $W \le 1$–$3$ J · cm$^{-2}$);

– the treatment procedure should involve no less than 5–6 pulses;

– the gap between pulses should exceed the time needed for spread of ionized desorption products that is no shorter than 50–100 μs;

– the pulse repetition frequency should be no higher than 10 kHz.

Laser processing of optical elements in this mode increases the threshold of optical damage of the surface at pulsed irradiation up to 6–8 J · cm$^{-2}$ and the service life at continuous irradiation by three to five times.

The increase in reliability and the service life of IR optics can be also obtained by optimizing the design of laser optical elements and decrease in unevenness of the incoming laser radiation.

The design of the segmented and sectioned laser windows allows the irradiated volume of the optical element to be decreased by 10–50 times and, consequently, its specific laser load to be increased.

With the aperture of 30 cm, a nine-element segmented window with the 0.5 probability of optical element damage allowed transmission of laser radiation pulses with the duration ~1 μs and the energy up to 5 or 6 kJ, while the single-element window transmit pulses with the energy up to 3.5 kJ. As a result of optimizing the design of the segmented laser window, the technological series of windows for the apertures from 120 to 450 mm transmitting laser pulses with the energy up to 25 kJ and the mean power up to 100 kW in the repetitively pulsed mode has been developed (Fig. 2).[1]

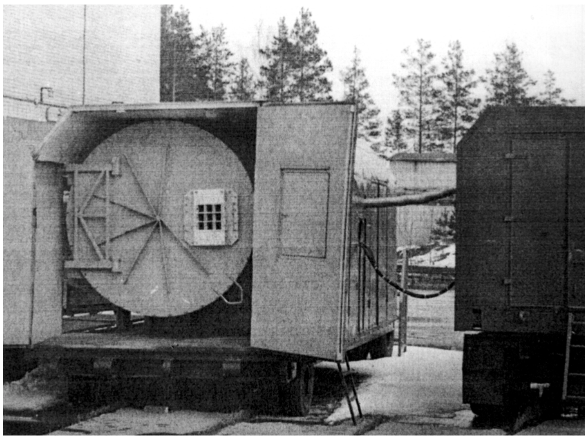

**Fig. 2.** Segmented window with the aperture 450 × 450 mm installed on a vacuum chamber.

The design of the segmented window allows a stepwise decrease of the pressure difference at the side of an optical element due to intermediate volumes between optical elements.

The experimentally found dependence of laser destruction threshold on the optical element thickness $h$ at the unchanged aperture indicates that for $d = 150$ mm the decrease of $h$ from 20 to 12 mm allows the intensity of the incoming radiation to be increased by 1.4–1.6 times. The segmented mirror of a two-chamber vacuum bench (Fig. 3) with the aperture of 250 mm transmitted the radiation with the intensity 1.2–1.5 times higher than the single-crystal one without destruction of the optical element.

The wide-aperture laser radiation is characterized by the presence of the so-called “hot spots” with anomalously high intensity, whose effect can lead to local damages with catastrophic destruction of an optical element.[1] Therefore, significant improvement of laser-radiation tolerance and reliability of laser transmitting optics can be achieved owing to higher quality of radiation.

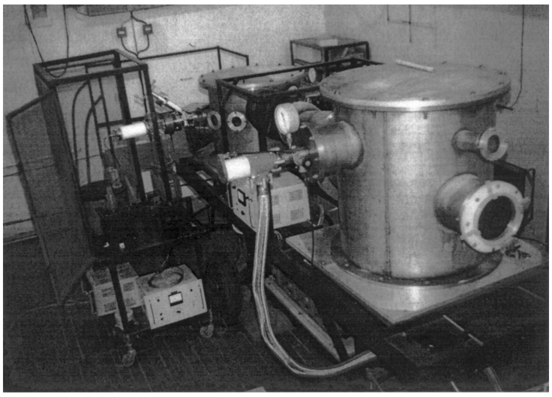

**Fig. 3.** Two-chamber vacuum bench with sectioned window.

It was found that a plasma torch formed near the entrance face shields the volume and exit face of the optical element from the effect of hot spots.[1] This finding formed the basis for development of the method of increasing the laser-radiation tolerance of an optical element by installing, in front of the optical element, a plate of the material transparent in the range of laser radiation wavelengths, but having the lower optical breakdown threshold (Fig. 4).

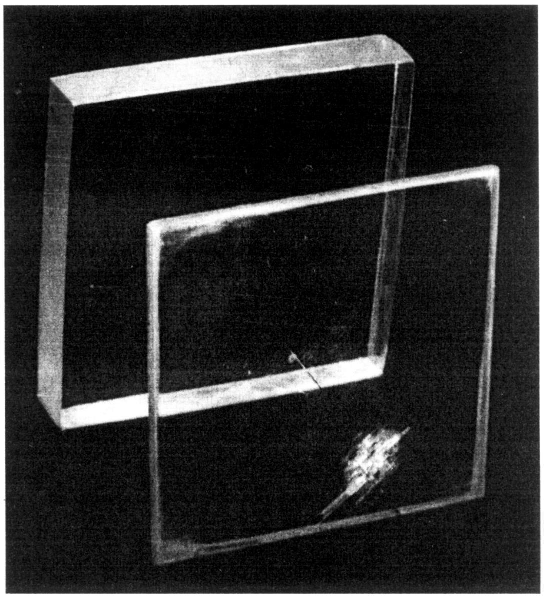

**Fig. 4.** Optical elements with the aperture 160 × 160 mm after propagation of the pulse with $\tau \sim 1$ μs and $W \sim 12$ J·cm$^{-2}$ through them.

The damage threshold of optical elements can be increased by 20–30% due to burning-out of hot spots on the plate, which considerably decreases the probability of their damage at the below-threshold intensity of the laser radiation. Besides, it becomes possible to use optical elements at $W$ two to three times exceeding the damage threshold values without risk of catastrophic destruction of optical elements, which turns out to be significant when performing works under deep vacuum.

The unevenness of the wide-aperture radiation can be decreased through application of raster mirror systems.

A laser system has been developed for input of high-power wide-aperture radiation into a sealed cell. This system includes two raster mirrors and an input window in the form of a collecting lens (Fig. 5).

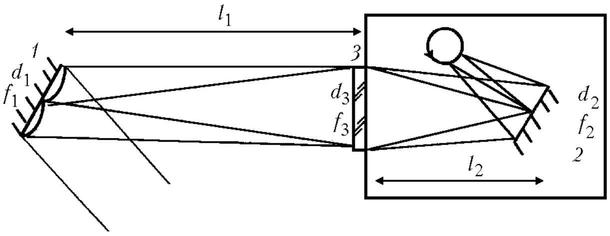

**Fig. 5.** Two-mirror optical system for entering a wide-aperture laser radiation into a sealed cell.

The first raster system on the optical path of laser radiation has convex mirrors with the focal lengths $f_1$ and the clear aperture diameter $d_1$ that defocus hot spots and sum up the mirror images in the plane of the input laser window. The input window having the light size $d_3$ and the focal length $f_3$ constructs the geometrically similar image of the first raster system having the clear aperture diameter $d_2$ inside the cell at the distance $l_2$. The second raster system is set in the plane of this image and used for formation of laser radiation in the plane of an irradiated object. The second raster system may have mirrors with any focal length $f_2$.

The optical arrangement is calculated using the equation of segments of parallel optics under the condition that the angle between the axes of laser beams coming from two neighboring mirrors of the first raster system should be no more than 4–5°, i.e., $d_1/l_1 \leq 10^{-1}$ rad (Ref. 1). The efficiency of using this scheme is illustrated in Fig. 6.

Depending on the peculiarities of using the optical elements, their reliability and service life can be increased based on combination of production and the design methods.

For a repetitively pulsed $CO_2$ laser, the design of a window with the aperture 150 × 150 mm and a central support of an optical element of deformation-strengthened KCl has been developed, and this increased the service life of optical elements up to 2 years.

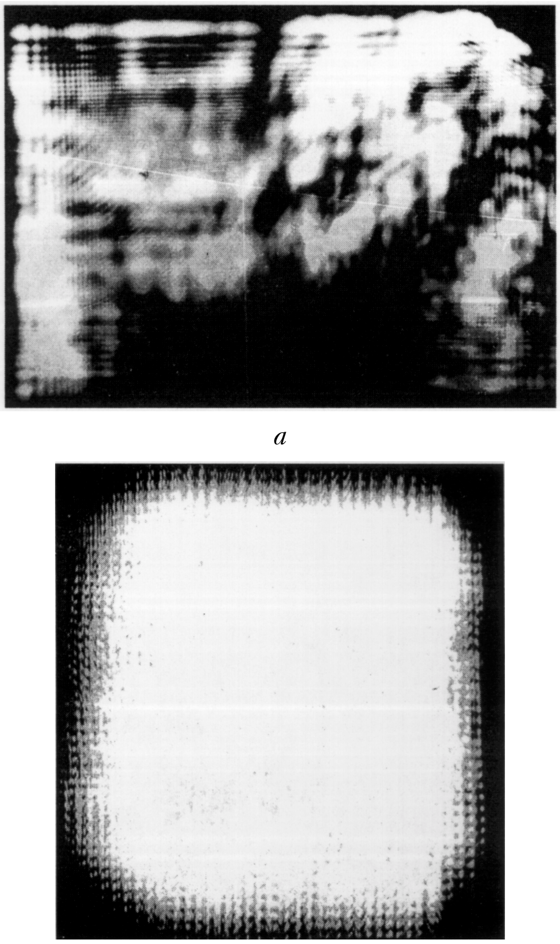

**Fig. 6.** Photographs of burnt spots on calibrated photographic paper at the entrance of two-mirror optical system (*a*) and in the plane of the irradiated object (*b*); the spot size is 30×20 cm and 10×10 cm, respectively.

For cw and repetitively pulsed lasers with the mean output power of 1–10 kW, a universal laser window with an attached annealing furnace allowing automatic temperature control, as well as recovery annealing of the optical element has been designed. The thermal attachment is used as a desiccator-heater, thus providing for the following advantages of the laser window:

– the optical element is continuously maintained at the increased temperature, which excludes the possibility of water adsorption, decreases absorption in the near-surface layer, and increases the laser-radiation tolerance and the service life;

– preliminary heating of the optical element and automatic regulation of the heat application to the thermal attachment allows maintaining the continuous temperature conditions of the optical element and decreases temperature gradients at the time of application and removal of laser load;

– as thermoinduced stresses are accumulated, it is possible to perform high-temperature annealing of the optical element without its disassembly.

Such a design allows annealing after every working cycle of irradiation of the optical element with internal stresses maintaining below the critical values, which decreases the time of crystal detention at high temperature down to 1–2 h. A mode of cyclic annealing has been developed that allows the internal stresses in KCl single crystals to be decreased from 18–24 to 12–14 kg $\cdot$ cm$^{-2}$. In this case the total duration of thermal processing of an optical element does not exceed 6–8 h, which is consistent with technological intervals of most production processes. The life time of optical elements of KCl and NaCl single crystals in a laser window with the thermal attachment increases by no less than an order of magnitude.

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